“Wound Field and Hybrid Synchronous Machines for EV Traction with Brushless Capacitive Rotor Field Excitation”

2018 DOE Annual Merit Review

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Illinois Institute of Technology

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Project ID: elt092

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Overview

Timeline

- Start Date: 10/1/17
- End Date: 3/31/19
- Percent Complete: 70%

Barriers

- Cost of EV traction motors has been resistant to decrease
- Rare earth permanent magnet (PM) market has been subject to significant price and supply volatility
- Power factors of IPMSM and IM increase power electronics cost

Budget

- Total project funding
  - DOE's Share: $999,752
  - Partner's Cost Share: $112,955
- FY 17 DOE Funding: $438,561
- FY 18 DOE Funding: $383,679

Project Partners

- Illinois Institute of Technology
  - Lead
- University of Wisconsin-Madison
- Lucid Motors (Atieva)

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Relevance/Objectives

Overall

- Develop cost effective wound field synchronous machines (WFSMs) and hybrid excitation synchronous machines (HESMs) which meet DOE cost and performance metrics by 3/30/19
  – Final FY19 prototype targets: peak power ≥ 55 kW, continuous power ≥ 30 kW, specific power density ≥ 1.6 kW/kg, volumetric power density ≥ 5.7 kW/l, Cost ≥ 4.7 $/kW.
- Develop cost effective and robust capacitive power coupler (CPC) for brushless rotor field excitation power transfer
- Create advanced torque/current regulation algorithms for WFSMs and HESMs
- Evaluate the performance and cost of final prototype wound field or hybrid excitation synchronous machine using the capacitive power coupler

This Period

- Demonstrate capacitive power coupler transfers $P_{avg} \geq 300$ W and $P_{peak} \geq 600$ W.
- Prototype WFSM or HESM achieves peak power ≥ 55 kW, continuous power ≥ 30 kW, specific power density ≥ 1.5 kW/kg, volumetric power density ≥ 5.0 kW/l

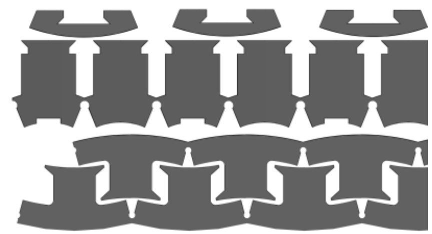
Milestones

Milestones & G/No-Go Decision Points	Date	Status
Identify tradeoffs between P.M. quantity/material and capacitive power transfer requirements	12/30/16	Complete
Initial journal bearing capacitive power coupler (CPC) prototype 1 meets initial power transfer metrics in s	3/31/17	Complete
Construction of best in class full power WFSM or HESM rotor prototype 1 complete	9/5/17	Complete
Best in class full power WFSM or HESM prototype 1 meets reduced peak power metrics using brushes during dynamometer testing	12/25/17	Complete
Journal bearing CPC prototype 1 transfers $P_{avg} \geq 300$ W and $P_{peak} \geq 600$ W during bench testing	9/29/17	Complete
Rated field current through journal bearing CPC prototype	12/31/17	Complete
PCB CPC design meets initial power transfer metrics	3/30/18	Complete
Low scrap best in class WFSM/HESM design meets power density metrics in simulation	6/30/18	On-going
Construction of full power low scrap best in class WFSM/HESM prototype complete	9/28/18	On-going
PCB CPC prototype transfers $P_{avg} \geq 300$ W and $P_{peak} \geq 600$ W during bench testing	9/28/18	On-going
Full power low scrap best in class WFSM/HESM prototype meets final power output metrics with brushes	12/31/18	On-going
Full power low scrap best in class WFSM/HESM prototype meets final power output metrics with CPC	3/15/2019	On-going
Full power low scrap best in class WFSM/PMWFSM with integrated brushless power coupler BOM achieves $\leq$\$4.7/kW target	3/29/2019	On-going

Approach

WFSM Cost Reduction Approaches

- Die compressed windings (targeting ~70% to 80% slot fill)
  - Flexible number of turns compared to bar/hairpin winding
  - Reduced AC losses at high frequency compared to hair-pin winding
  - Single thermal mass with no air voids
  - Potential to use aluminum wires with similar performance to 40 to 45% fill copper windings with significant cost and weight savings
  - Fractional slot concentrated winding maybe required for stator
- Low scrap designs (typically 40% scrap for IPMSMs)
  - Leverage cut-core and roll-up techniques on stator and rotors
  - Potential to utilize lower grade electrical steel in rotor

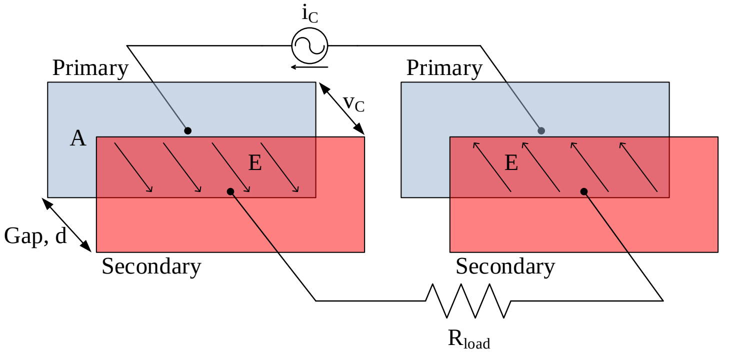


- Fully utilize machine's active materials
  - Refine in-house developed optimization tool
  - Explore the use of topological optimization
- High performance controls development for WFSMs

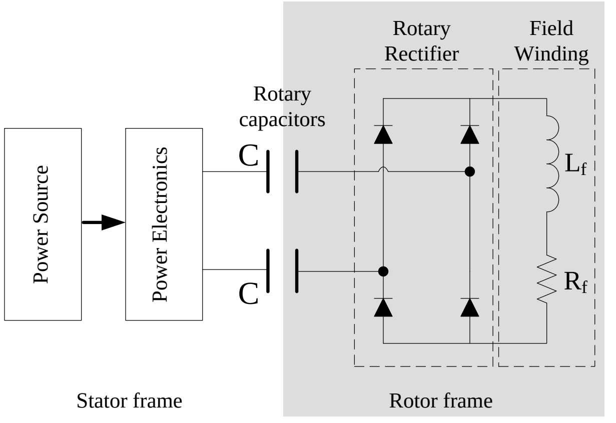
Approach

- Capacitive power transfer (CPT) to rotor field winding
  - Power transfer to WFSM field winding through electric field between rotary capacitors

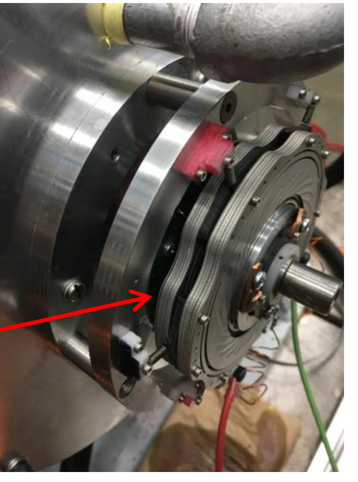
Basic Concept



CPT for WFSM Concept



  - No need for back iron
  - Electric flux lines terminate on charge, limited field outside of gap
  - Previous project used stacked anodized aluminum disks with spiral groove to form axial flux hydrodynamic coupling capacitors



Approach

<u>Lower the cost of the capacitive power coupler</u>

- Increase the frequency (MHz) to shrink required capacitance (A/Hz)
- Lower losses in the converter by operating in resonant soft switching
  - Reduced thermal management and reduced switch rating
- Mechanically simpler capacitive coupler PCB plates with tank circuit or journal bearings
  - Reduced capacitance

<u>Develop Hybrid Excitation Synchronous Machines (HESMs) to lower field power requirements</u>

- Bias the flux for most common operating point in drive cycle
- Reduce the amount of PM material compared to full PM machines
- Extend constant power speed range compared to full PM machines

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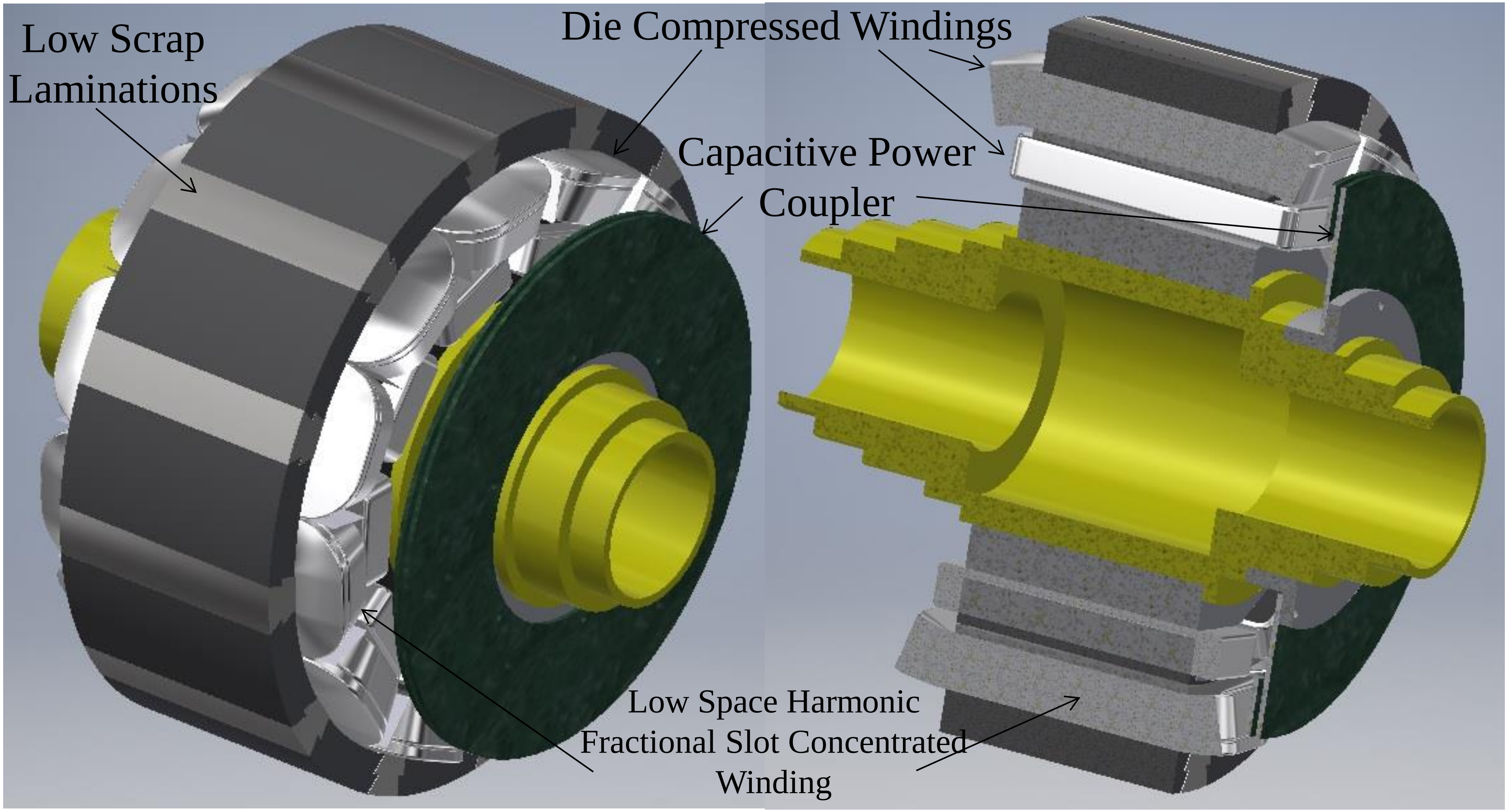
Overall Machine and CPC Concept



WFSMs and HESMs Prototype Development Plan

- Incremental development approach
  - Each prototype will target a specific cost reduction approach/technology
  - Every prototype is targeted to meet power conversion metrics

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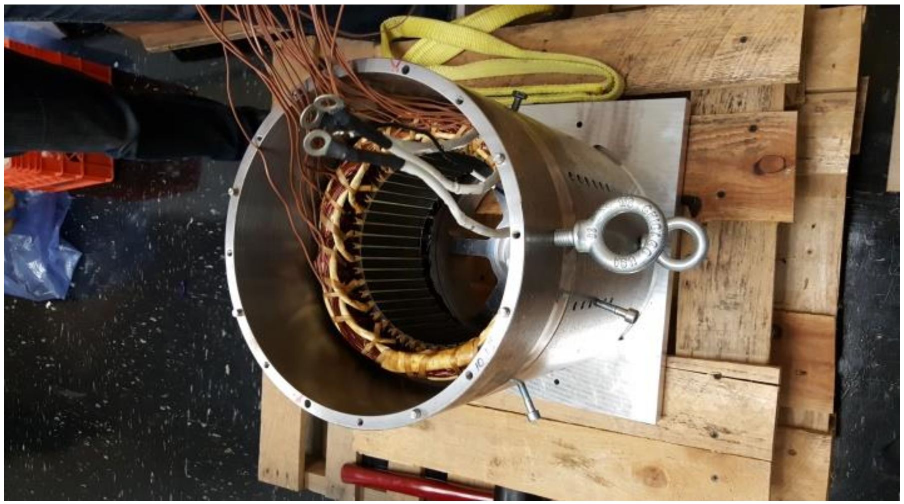
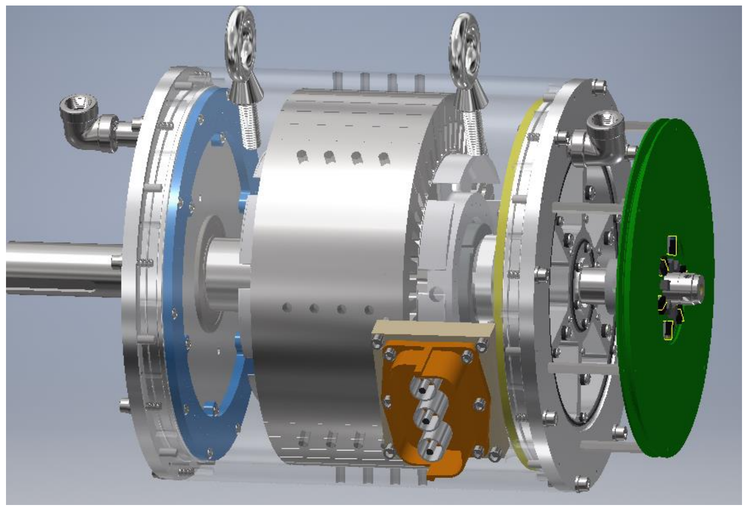
- Prototype 1: Increased power density classical WFSM (Finished)
- Prototype 2: Parallel flux dual rotor HESM (Finished)
- Prototype 3: WFSM with die compressed field winding (75% Complete)
- Prototype 4: New HESM rotor (Design complete)
- Prototype 5: Low scrap WFSM/HESM stator (Initial design stages)
- Prototype 6: Low scrap WFSM/HESM stator and rotor with die compressed windings (potentially aluminum windings)

- Integrate prototypes 2,3 & 6 with CPC

Technical Accomplishments - Baseline WFSM Prototype

- New baseline WFSM prototype rotor constructed and dynamometer tested
  - 83 kW output at 4000 RPM with torque of 196 Nm
  - Old stator; OD = 254 mm, old stator stack length = 92 Nm
  - Rotor stack length = 106 mm
  - Output limited by stator saturation
- New stator design and housing
  - New stator; OD = 254 mm, stator stack length = 106 mm
  - Still requires dynamometer testing
  - Simulated 112 kW output at 4000 RPM with torque of 270 Nm
  - New oil spray cooling system and observational windows

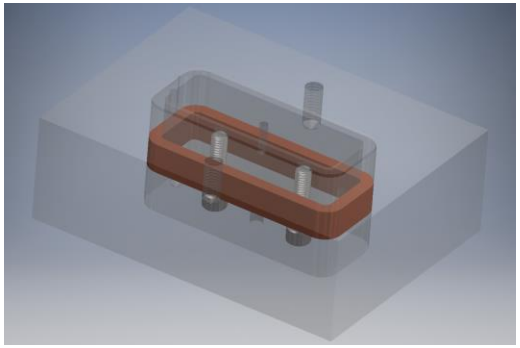


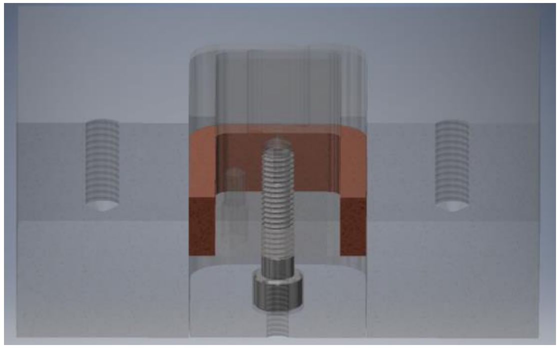


Technical Accomplishments – Die Compressed Windings

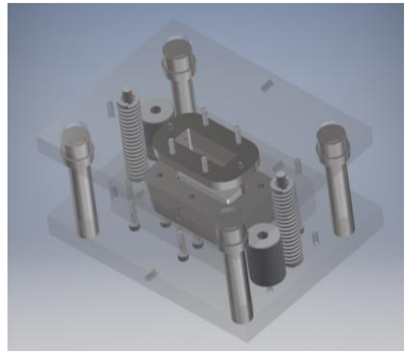
- Die compressed windings originally proposed by A. G. Jack et. Al. for PMSM
- Design of two dies for compressed field winding completed
- Manufacture of simplified design completed
- Copper and aluminum field coils being prototyped

Initial rectangular field coil die





Die design for shaped field coil



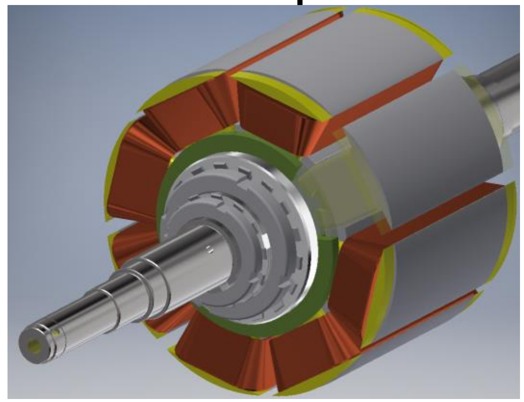
Rectangular die components

Riehle 800,000 lb press

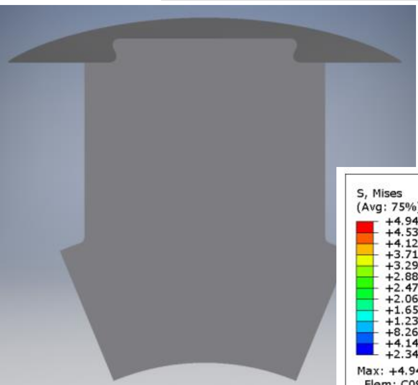
A. G. Jack *et al.*, "Permanent magnet machines with powdered iron cores and pre-pressed windings," in *Conference Record of the 1999 IEEE Industry Applications Conference*, 1999, pp. 97–103.

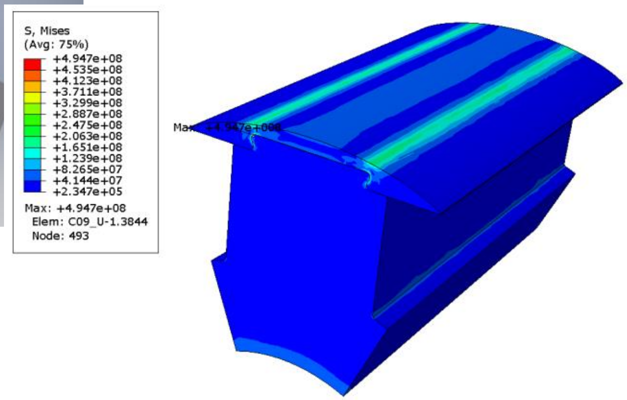
Technical Accomplishments - WFSM Rotor Mechanical Design for Compressed Field Winding

- Mechanically robust joint in rotor pole neck to insert compressed field coil
  - Wind on bobbin, compress, insert over rotor pole neck, insert pole end shields, and axial retainer
  - Dovetail and fir tree joints studied in pole cap and neck/yoke interface for 12 kRPM max speed

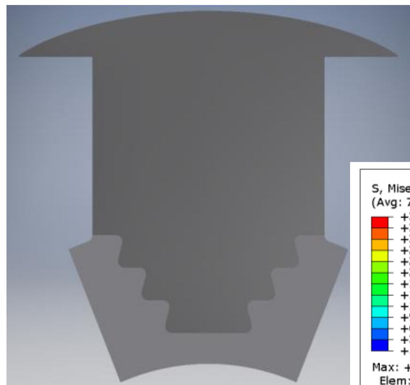


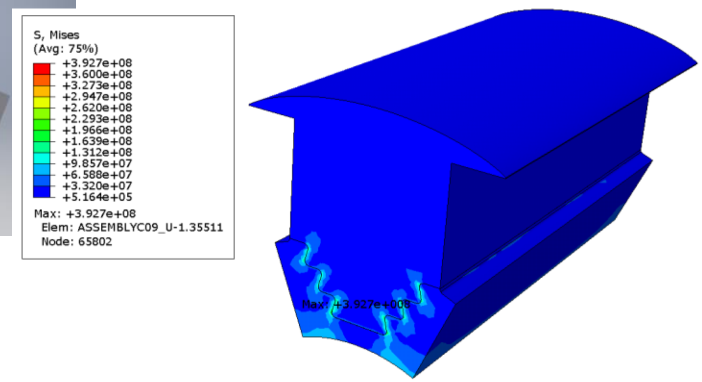
Example pole cap dovetail joint





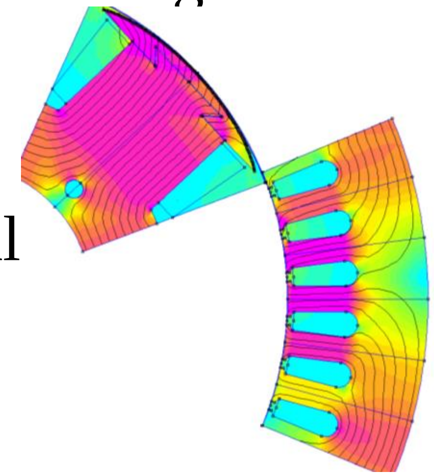
Example neck/yoke fir tree joint



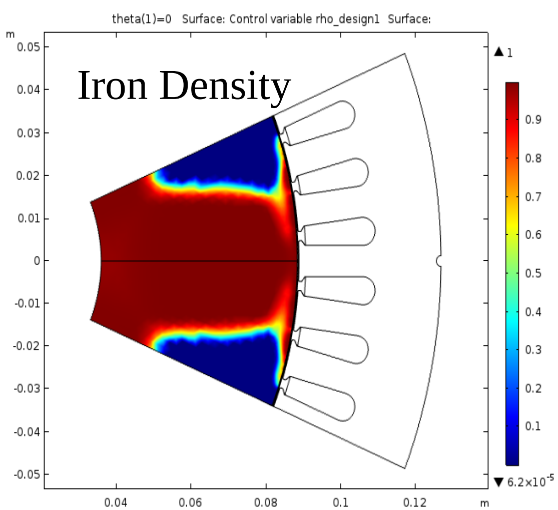


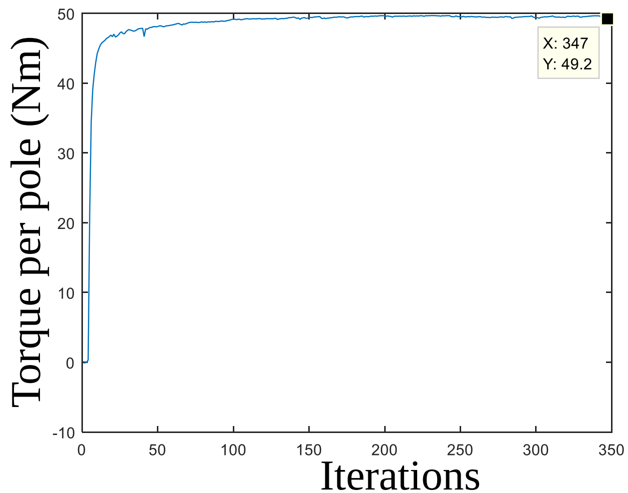
Technical Accomplishments - Full Utilization of Active Materials

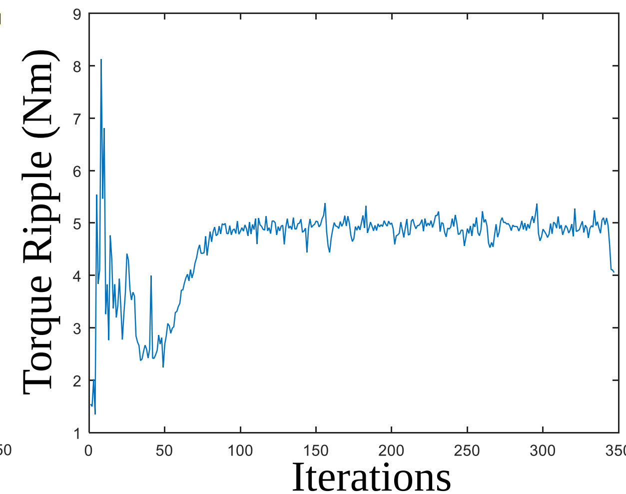
- Extended in-house WFSM/HESM optimization suite for magnetic joints and die compressed windings



- Developed electromagnetic multi-material topological optimization of WFSM rotors
  - Based on SIMP technique
  - Also works for IPMSM rotors







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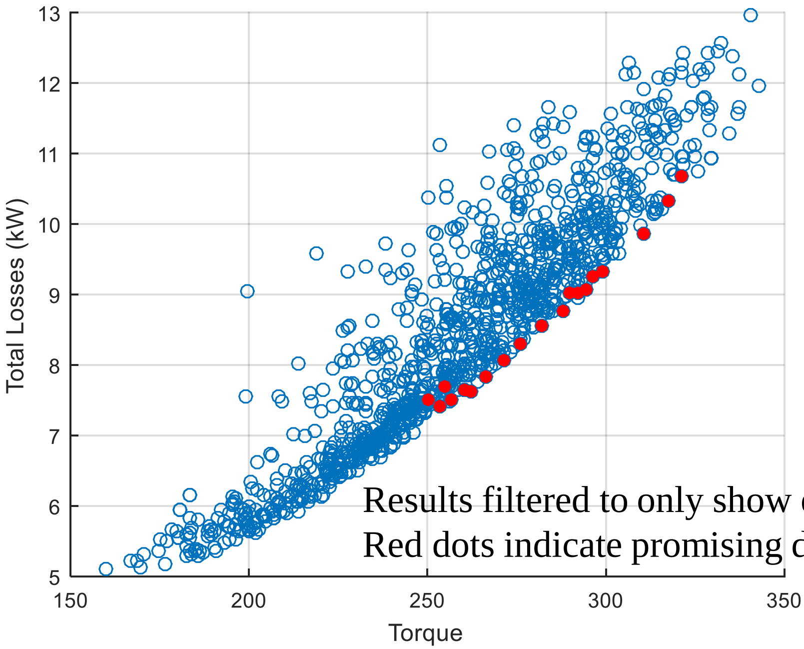
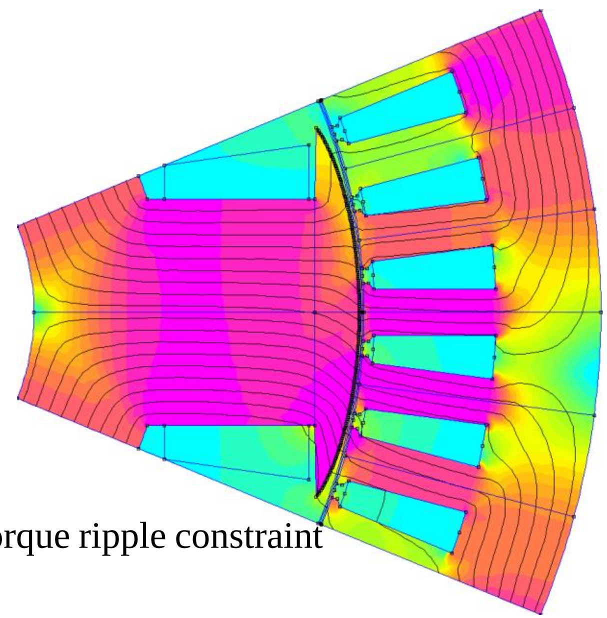
Technical Accomplishments - Electromagnetic and Thermal Optimization

- Extensive optimization runs completed for optimizing stator and rotor electromagnetics for rectangular compressed coil and regular field windings
  - Copper and aluminum field windings
  - Distributed winding single layer (q = 2), distributed winding mixed layer, and bar/hairpin windings
- Improved oil spray cooling analysis and experimental validation

<u>Rotor: Die Compressed Au Winding</u>
<u>Stator: Distributed Single Layer Winding</u>



<u>Representative Copper Rotor</u>
<u>Bar/Hairpin Copper Stator</u>



Results filtered to only show designs T_{ripple} <10%
Red dots indicate promising designs which meet torque ripple constraint

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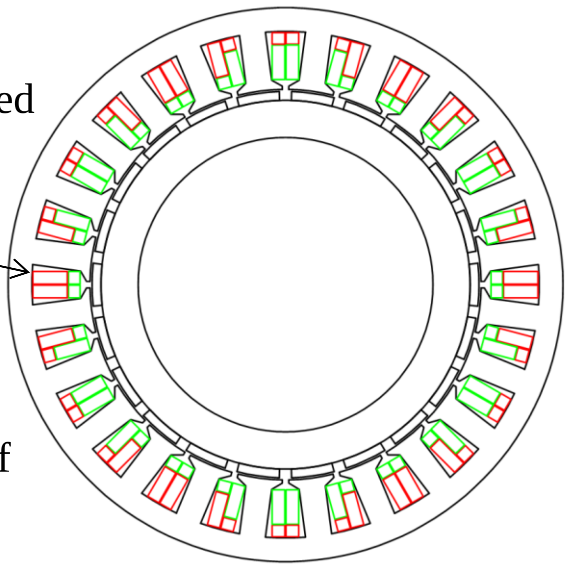
Technical Accomplishments - New Winding Optimization Method

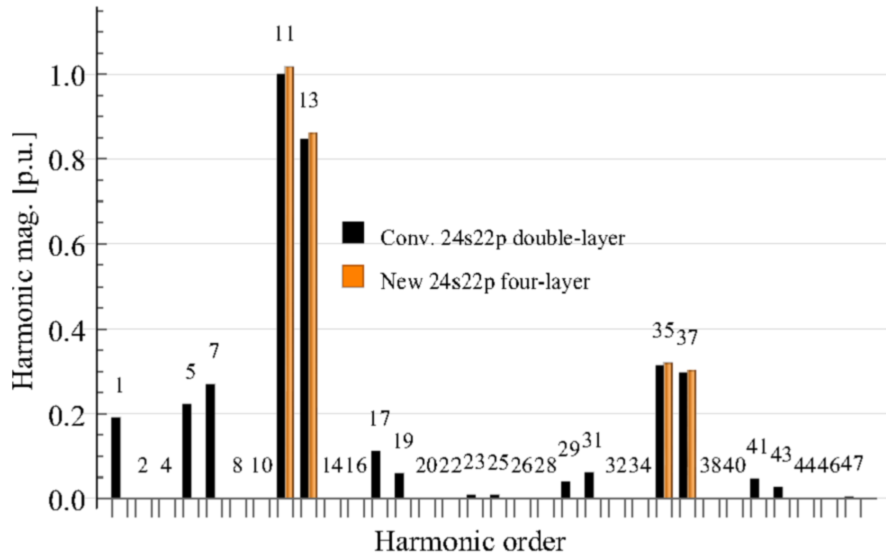
- Combination of die compressed windings and low scrap laminations likely requires stator fractional slot concentrated windings (FSCWs)
- FSCWs generally have high space harmonic content limiting use to low/medium speed machines
- Unified mathematical winding representation that allows for variable number of turns and slot angles created
- Example new 24-slot, 22-pole FSCW with reduced harmonic content

4 layer concentrated winding

Potential die compressed windings

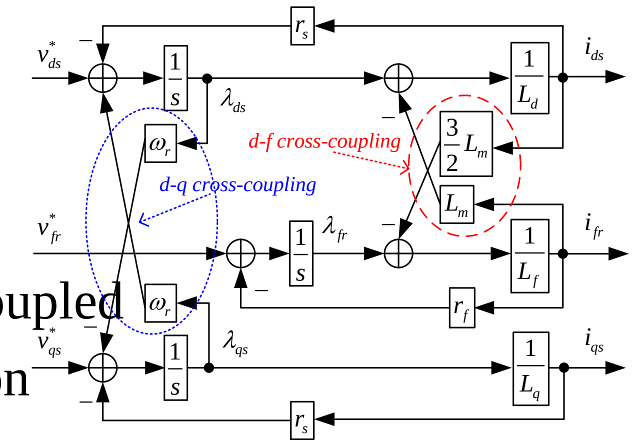
Variable number of turns

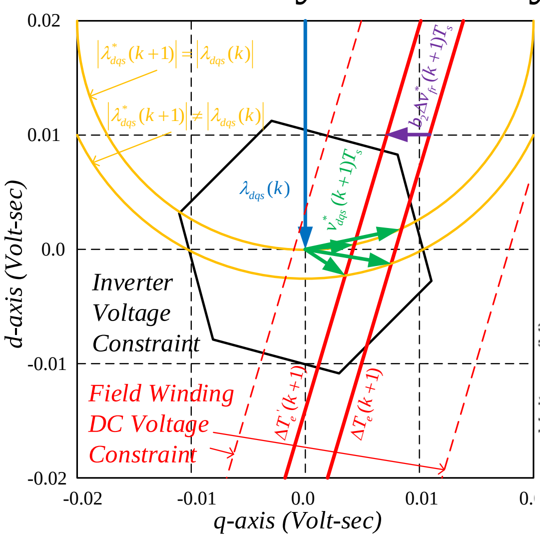




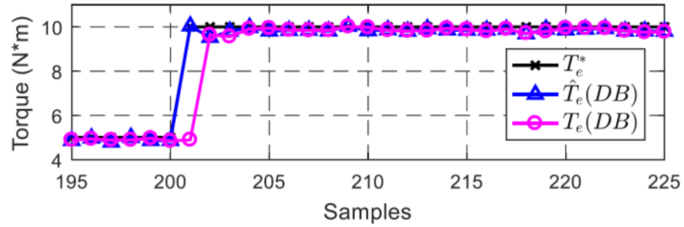
Technical Accomplishments - High Performance WFSM Controls

- WFSMs have an extra state cross-coupling compared to other AC machines: d-f coupling & d-q coupling
- Deadbeat-direct torque and flux controller developed for WFSMs
  - Torque, stator flux linkage, and rotor flux linkage decoupled
  - Finite settling step response in voltage limited operation
  - Steady state unity power factor operation

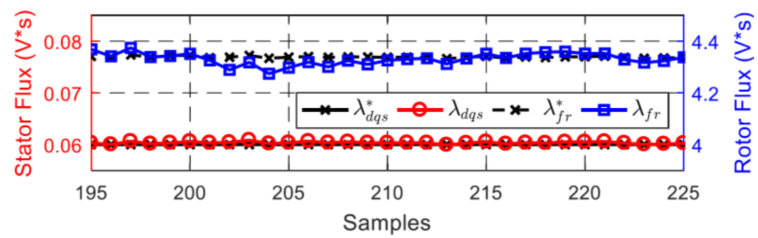




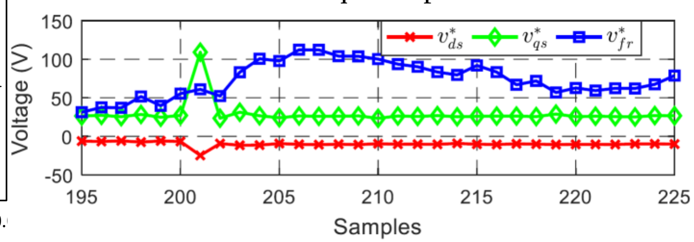
Graphical solution of DB-DTFC for WFSM



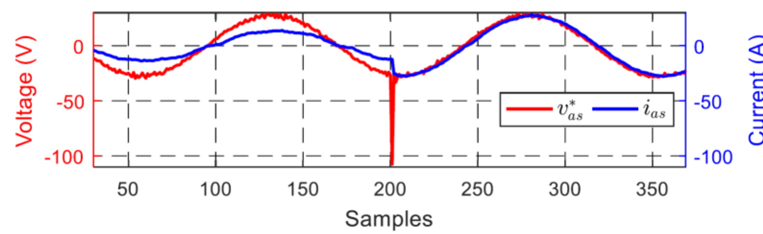
Torque responses



Flux linkage responses



Voltages applied



Phase current and synthesized phase voltage command

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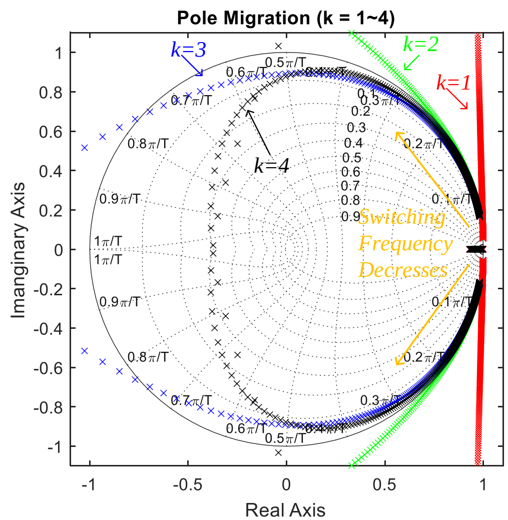
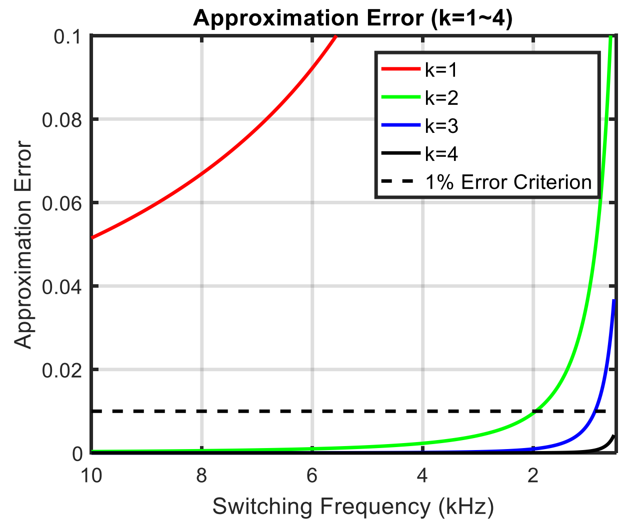
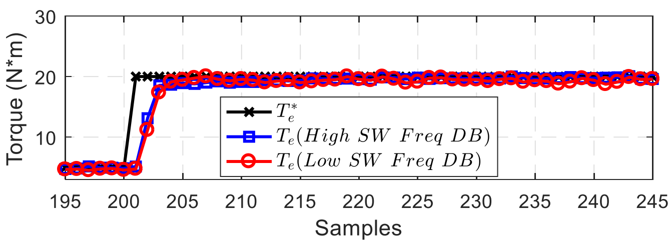
Technical Accomplishments - Low Switching Frequency WFSM DB-DTFC

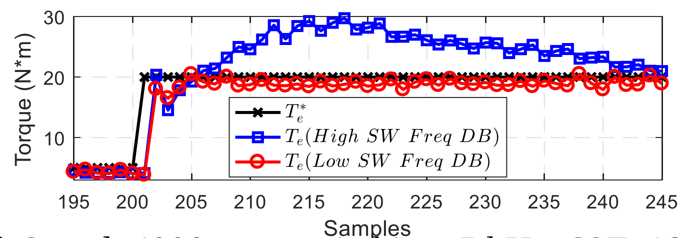
- Enhancements to WFSM DB-DTFC for operation at low switching to fundamental frequency ratios (S2F)
- Taylor series approximation of sampled Laplace discrete time models
- Four terms for discretization convergence and less than 1% approximation error







(a) Speed: 1000 rpm, switching: 10 kHz, S2F: 150



(b) Speed: 4000 rpm, switching: 5 kHz, S2F: 18.75

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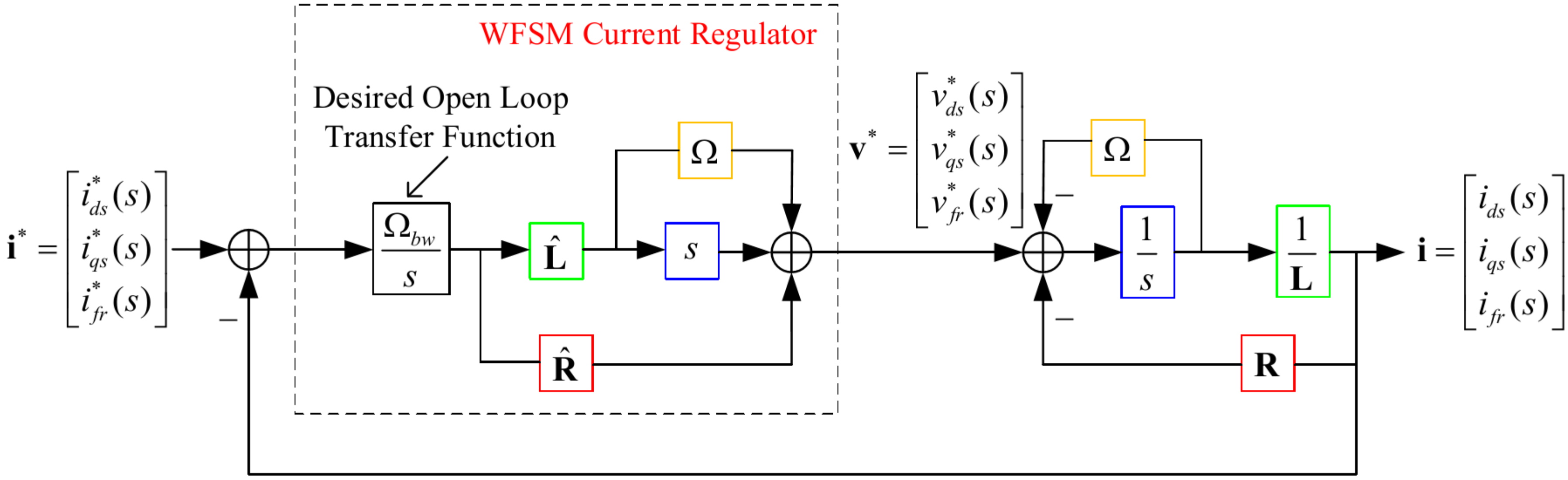
Technical Accomplishments - Classical WFSM Decoupling Current Regulator

- Matrix instead of complex vector approach to account for field current
- Decouples all three axes
- Allows for pole-zero cancellation
- Experimental testing this summer



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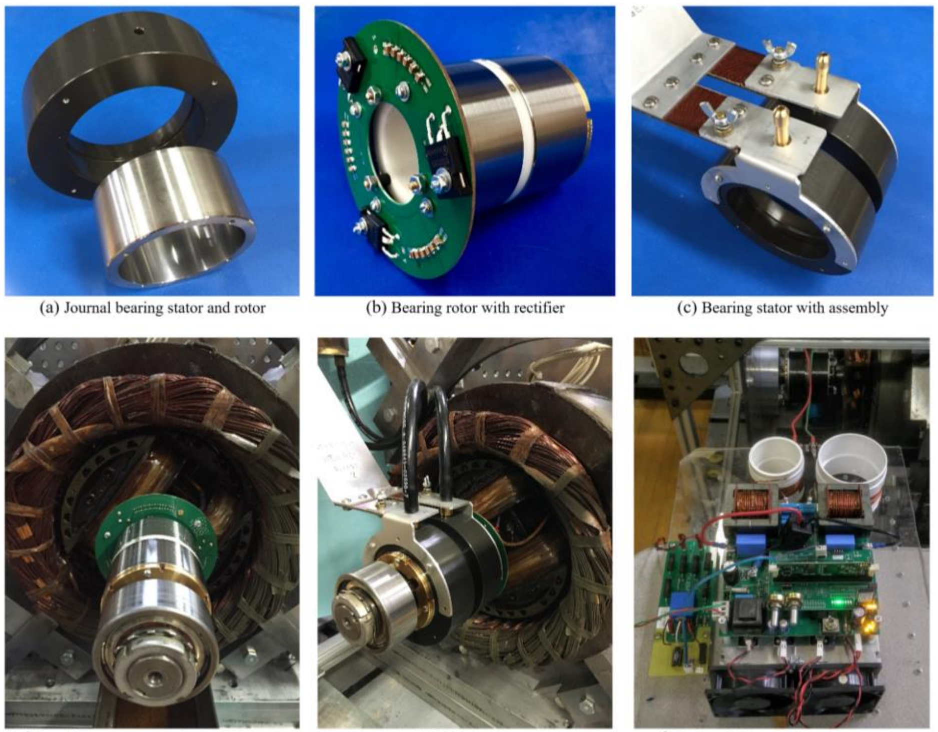
Technical Accomplishments - Brushless Power Couplers

- Several brushless field winding power coupler topologies investigated
  - Journal Bearing CPC
  - Integrated LC PCB CPC
  - Large gap PCB CPC (focus going forward)

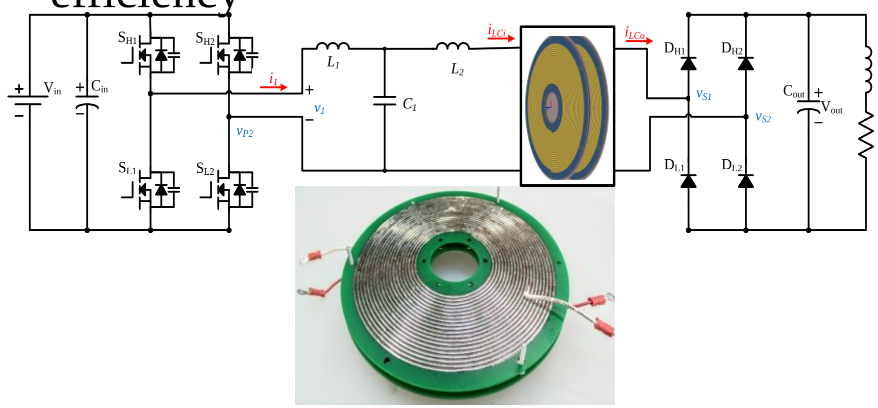
Journal Bearing CPC



(a) Journal bearing stator and rotor
(b) Bearing rotor with rectifier
(c) Bearing stator with assembly
(d) Bearing rotor mounted on WFSG rotor
(e) Assembled journal bearing setup
(f) Push-pull-Class-E inverter prototype

Integrated LC PCB CPC

- 2 double sided PCBs each forming capacitive dipole
- 2 dipoles couple capacitively
- Spiral trace adds magnetic coupling as well
- Proximity and skin effect losses lower coupler efficiency



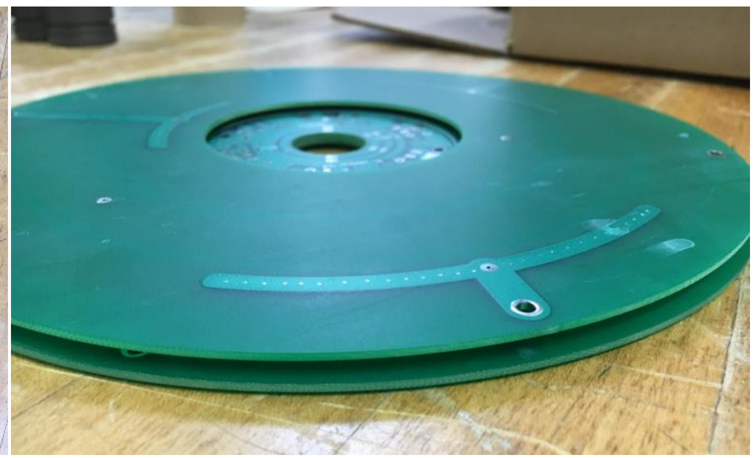
Technical Accomplishments - Brushless Power Couplers

- Large gap, 3 phase CPC constructed from 1 rotor PCB and 2 stator PCBs
  - Mechanical simple
  - Rotor sandwiched between stator PCBs
  - Low coupling capacitance (~450 pF); requires high frequency (2.5 A/MHz)
  - Losses observed where traces overlap on PCB due to formation of capacitance on same PCB

Double sided rotor

Single sided stator

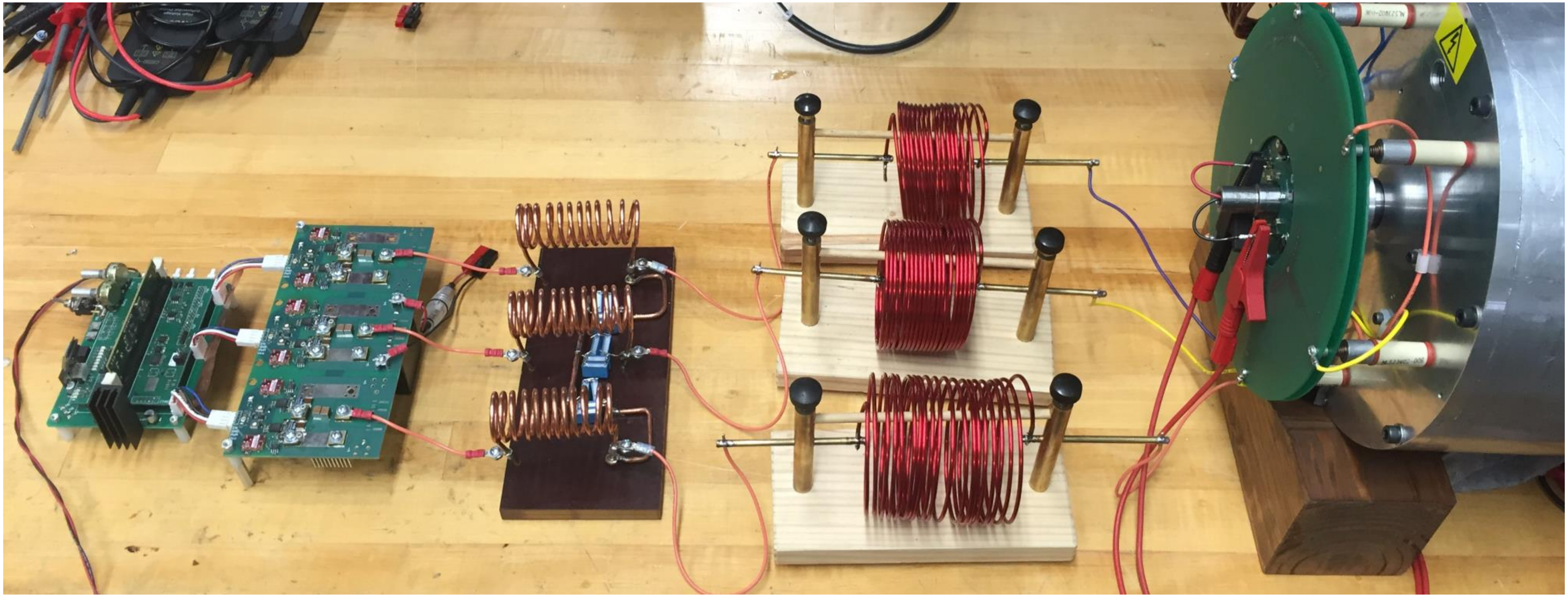
PCB Assembly



C. Liu, A. P. Hu and N. K. C. Nair, "Coupling study of a Rotary Capacitive Power Transfer system," *2009 IEEE International Conference on Industrial Technology*, Gippsland, VIC, 2009, pp. 1-6.

Technical Accomplishments - Overall Large Gap CPT Prototype Assembly

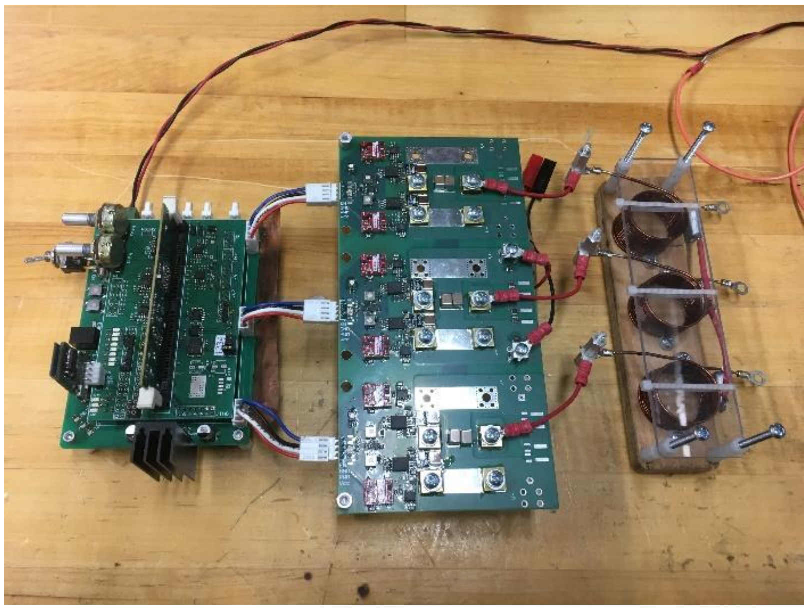
- Separately adjustable tuned inductors for each phase
- Future work to focus on compact inductor design
- Redesign of PCB CPC to improve capacitive balance between phases



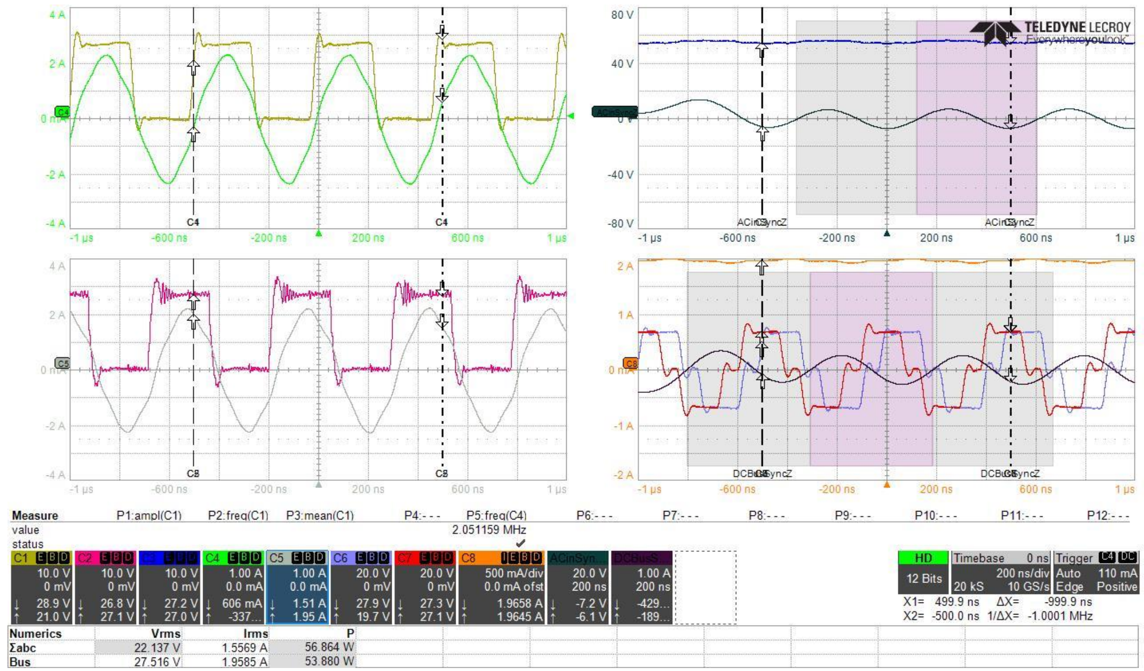
Technical Accomplishments - Capacitive Power Transfer Inverter

- 2 MHz, soft switching, GaN based 3 phase inverter for CPT
  - 150 V_{dc} link
  - Very high efficiency; measured up to ~99.8% (difficult to measure at these frequencies and efficiencies)

<u>Prototype</u>



<u>Measured Line to Line and DC Link Quantities at 1 A Field Current</u>



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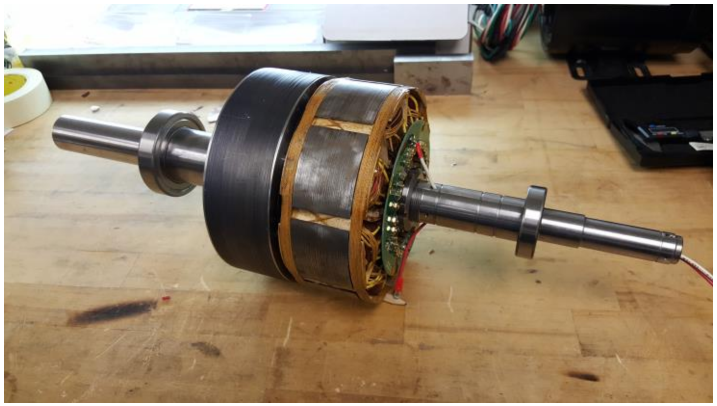
Technical Accomplishments - HESM Prototype 1

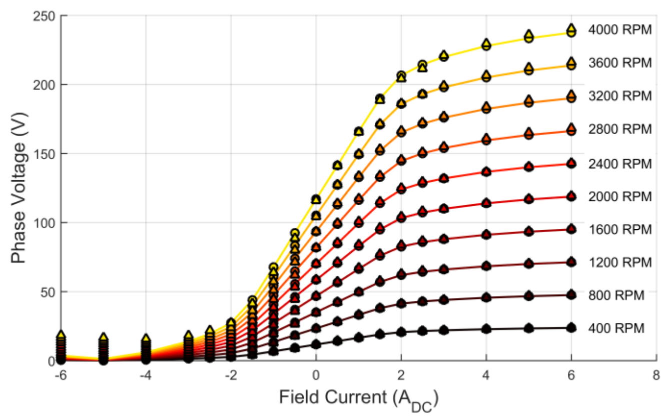
- Analytical sizing theory for HESMs developed
- Parallel hybrid dual rotor; V-bar IPMSM and wound field rotors

Stator OD	254 mm	Stack Length	106 mm	Peak Power	83 kW
Peak Torque	200 Nm	Base Speed	4000 RPM	Max Speed	12,000 RPM
Vol. Power Density*	15.3 kWl^{-1}	Spec. Power Density*	1.98 $kWkg^{-1}$	Torque Density*	36.8 Nml^{-1}

*Active Materials including core, windings, etc.

- Initial low power dynamometer testing completed
  - 10:1 open circuit CPSR potential measured
  - Increased efficiency compared to pure WFSM
  - Reduced field current requirement by 1/2





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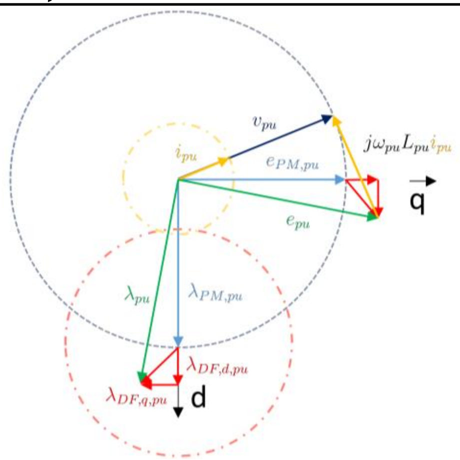
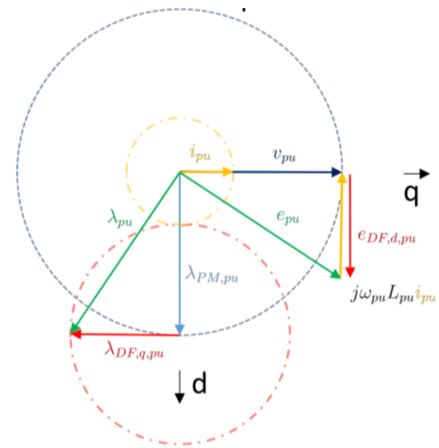
Technical Accomplishments - HESM Prototype 2

- New parallel flux dual rotor topology
  - Provisional patent filed
  - Design of new rotor complete and proof of concept prototype underway
- Flexible control possibilities
  - Wound field excitation axis can be orientation can be changed anywhere between q and d axes on the fly
  - Can be designed for infinite CPSR with unity power factor using either stator-rotor flux weakening or rotor flux weakening

<u>High Speed, PF=1, Stator-Rotor Flux Weakening</u>



<u>High Speed, PF=1, Rotor Flux Weakening</u>



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Response to Previous Year Reviewer's Comments

- Project was not reviewed last year

Collaboration and Coordination

- Illinois Institute of Technology
  - Electromagnetic, thermal, and structural design of WFSM and HESM
  - Development of control strategies for WFSM and HESM
  - Responsible for prototyping and testing of WFSM and HESM
- University of Wisconsin-Madison
  - Design and construction of capacitive power coupler
  - High power dynamometer testing
- Lucid Motors
  - Design reviews of WFSM, HESM, and CPC
  - Assistance with cost estimation
  - Donation of high power motor and mount plates for IIT dynamometer

Remaining Challenges and Barriers

- Design of low space harmonic windings for low to medium pole pairs with limited number of slots
- Mechanical design of low scrap segmented stator and rotor parts
  - Mechanical tolerances with prototype production processes
- Design for noise, vibration, and harshness of low scrap design
- Integration of WFSM and HESM concepts
- Reduction of PCB CPC losses by removing overlap of large traces
- Compact low loss inductor design
- Increase CPT DC link voltage for increased power transfer
- Further increase switching frequency for increased power transfer

Proposed Future Research

Budget Period 2 (Through 9/30/18)

- Revise design of PCB CPC
- Dynamometer test PCB CPC with WFSM prototype
- Finish dynamometer testing of HESM prototypes I & II
- Complete construction of WFSM prototype with die compressed field winding
- Dynamometer test WFSM prototype with die compressed field winding
- Design low scrap WFSM/HESM compatible with die compressed windings
- Construct low scrap WFSM/HESM with die compressed windings
- Experimentally validate WFSM decoupling current regulator

Budget Period 3 (Through 3/30/19)

- Dynamometer test low scrap WFSM/HESM with die compressed windings using brushes
- Dynamometer test low scrap WFSM/HESM with die compressed windings using PCB CPC
- Detailed cost evaluation of final design

Any proposed future work is subject to change based on funding levels

Summary

- Relevance
  - WFSMs and HESMs offer a low system cost path for widespread adoption of EVs
    - Brushless and no or reduced permanent magnet usage
    - Unity power factor operation to reduce inverter kVA rating
- Approach
  - Die compressed windings for high slot fill and potential use of aluminum
  - Low punching scrap design with low space harmonic content FSCW
  - Capacitive power transfer using mechanically simple PCBs
- Technical Accomplishments
  - Initial field winding compression die prototyped
  - New winding optimization theory developed
  - Two HESMs prototyped with one provisional patent filed
  - New high performance WFSM torque control algorithms
  - Mechanically simple PCB CPC and 2 MHz GaN inverter

FY2018 WFSM/HESM Targets Have Been Met

Metric	Target
Peak Power (kW)	55
Cont. Power (kW)	30
Specific Power Density (kW/kg)	1.5
Vol. Power Density (kW/l)	5.0

- Future Work
  - Redesigned PCB CPC and inductors
  - Design and testing of prototype of low scrap WFSM/HESM with die compressed windings

Technical Back-Up Slides

High Sample Rate DB-DTFC Block Diagram